Low power and lightweight UAV sensors for methane and other petrochemical tracers

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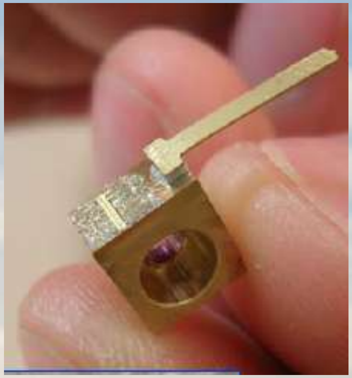


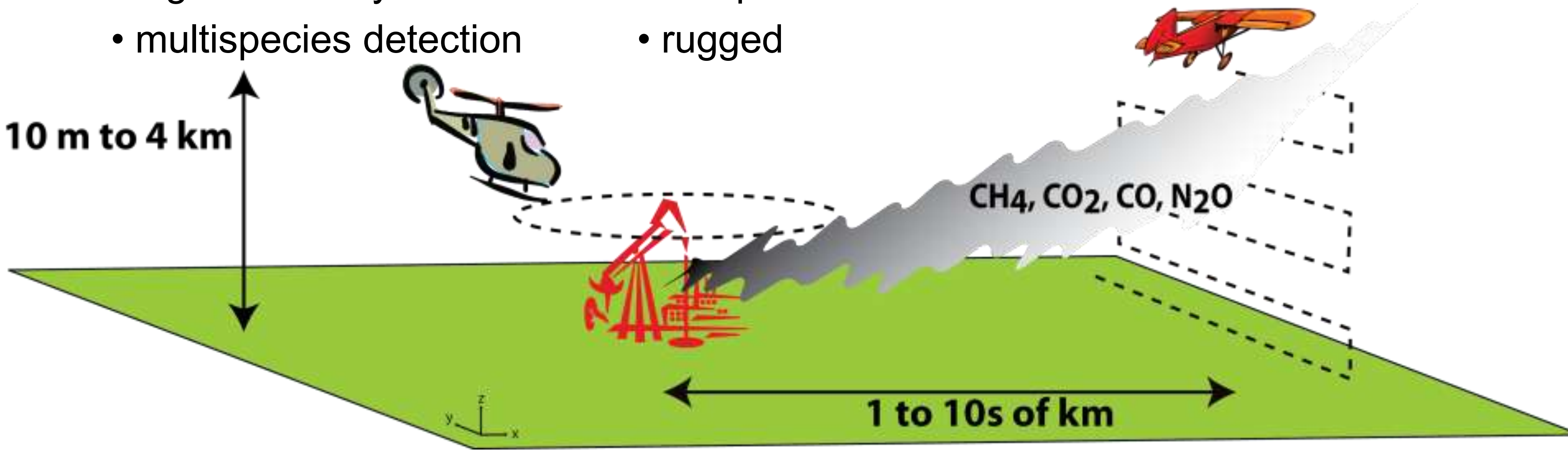
Why laser-based sensors for methane on UAVs?

Performance

- high sensitivity
- fast response (<< 1 Hz)
- high selectivity
- multispecies detection

Physical specifications

- low power (~ 1 W)
- low mass (~ kg)
- compact size
- rugged



Only large UAVs (e.g. NASA Global Hawk, SIERRA) fly existing laser-based sensors

To fully utilize UAV capabilities, need low power, light weight, compact sensors for smaller, cheaper, easier-to-deploy UAVs and UAV fleets

Our key innovations:

Vertical cavity surface emitting lasers
Open-path spectroscopy
Multiharmonic in-line stability system

Vertical cavity surface emitting lasers (VCSELs)

<u>Characteristics</u>

- Inexpensive for mass production
- Very large tuning range
- Low power draw (15 mW)
- Near-infrared

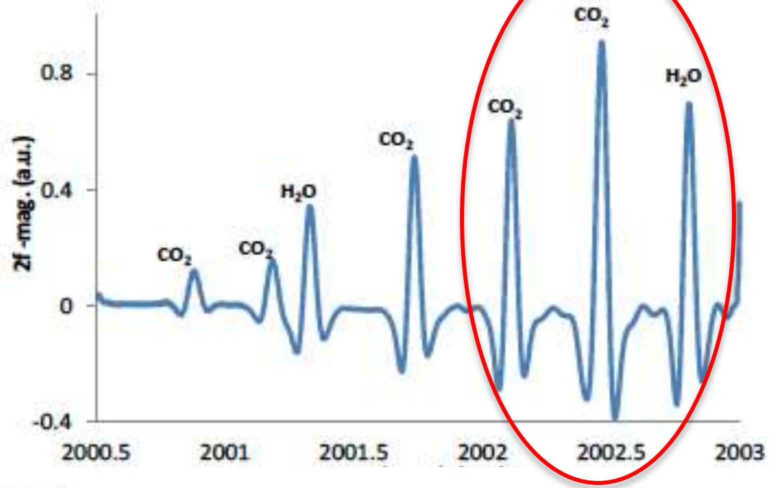
<u>Attributes for sensing</u>

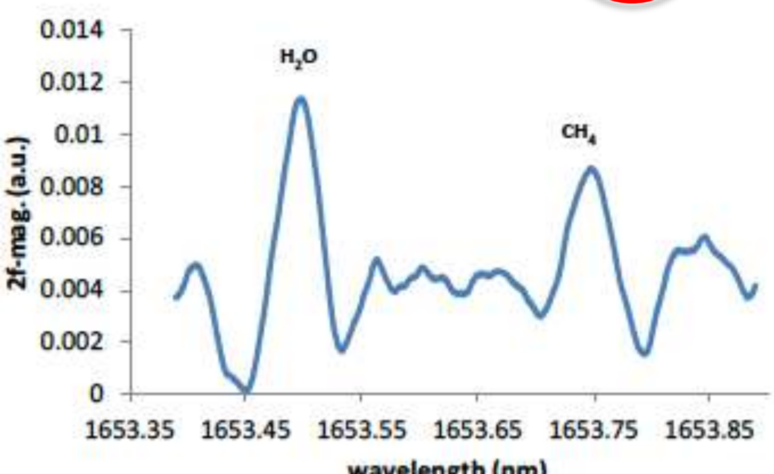
Inexpensive ($5/laser in large qty.)

Multispecies detection at high S/N

Low power, lightweight sensors

Spectrally clean absorption lines





Above: VCSEL hygrometer for NSF Gulfstream-V aircraft, >700 flight hours, 0-15 km, polar regions to tropics (Zondlo et al., *J. Geophys. Res.*, 2010)

Open-path detection: advantages and challenges

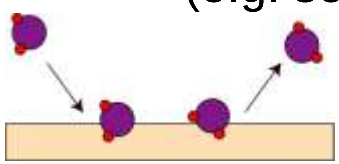
Open-path detection: gas sampled at ambient conditions, no sample handling

Advantages

sampling minimized
no gas handling
fast response
no inlet delay issues
no pumps (low power)
no phase re-partitioning

Challenges

spectroscopy over range of temp., pressure
need to know T, P in optical path
broad lineshapes, interferences from other gases
extreme, changing conditions
calibration
mirror/optics need to be relatively clean
(e.g. sea salt, dew/frost, bugs, mold)



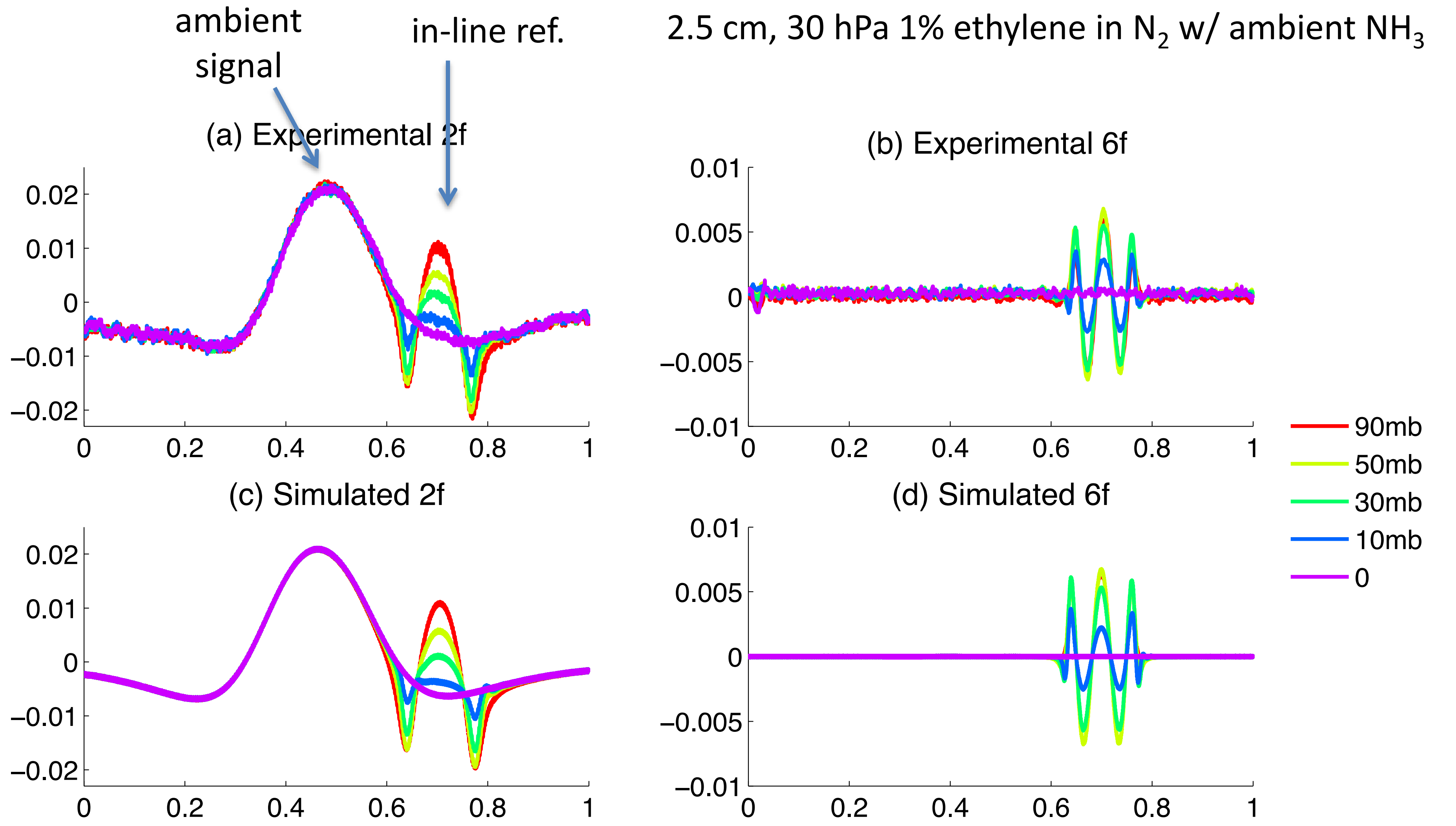
Open-path detection is essential for low power applications/sensors

and in rapidly changing environments (high spatial resolution)

Multiharmonic in-line stability system

Problem: Open-path configurations difficult to calibrate, subject to drift

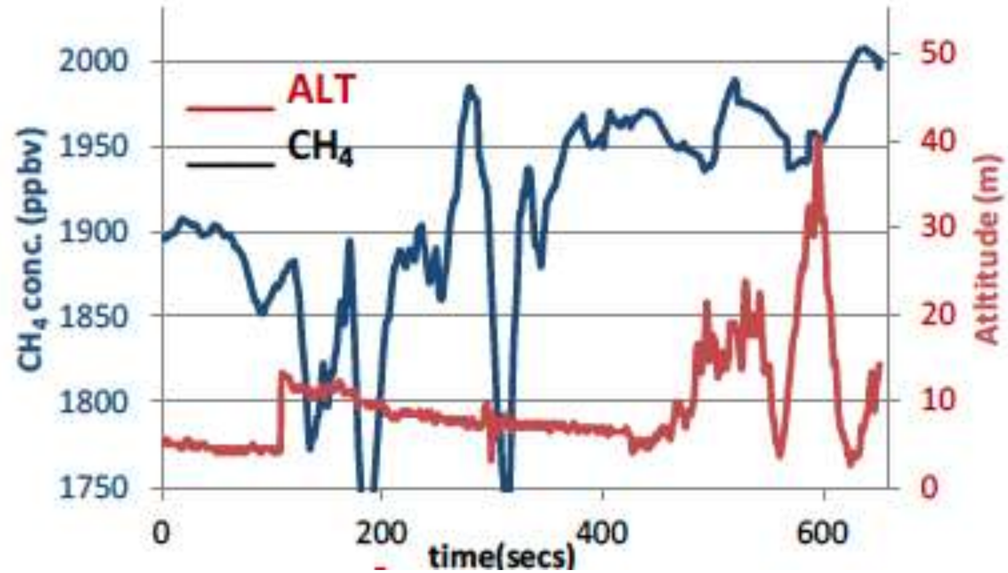
Solution: Continuous, in-line reference signal scanned; multiharmonic numerical fitting algorithm isolates reference signal from ambient



Reference signal unaffected by ambient absorption of interest in 6f detection

VCSEL sensors on UAV flight tests

- UAV test flight sensing, Nov. 2011 (UT-Dallas, David Lary)
- Successfully flew three sensors (CH_4, CO_2, H_2O) on T-REX Align 700E Helicopter
- 1.0-2.2 kg incl. batteries and all data acquisition/laser control electronics



Trace gas	Lower tropospheric range	Precision (1 Hz)	Mass/ Power
CO_2	350-450 ppmv	0.15 % (0.4 ppmv)	1.5 kg / 2 W
CH_4	1700-1900 ppbv	0.1 % (1.5 ppbv)	2.2 kg / 2 W
H_2O	50 – 50,000 ppmv	< 1 %	1 kg / 2 W

Khan *et al.*, *Remote Sensing*, 2012

UAV VCSEL-based CH_4 sensor

Flew 135 m above ground, 20 m s^{-1}, rapid turns and accelerations

Quantum cascade lasers: simultaneous N_2O, CO, and C_2H_2

<u>Characteristics</u>

- probes fundamental ro-vi bands
- mid-infrared spectral region
- fully cryogenic-free

<u>Attributes for sensing</u>

- high sensitivity, simple designs
- most key atmospheric species
- long-term operation

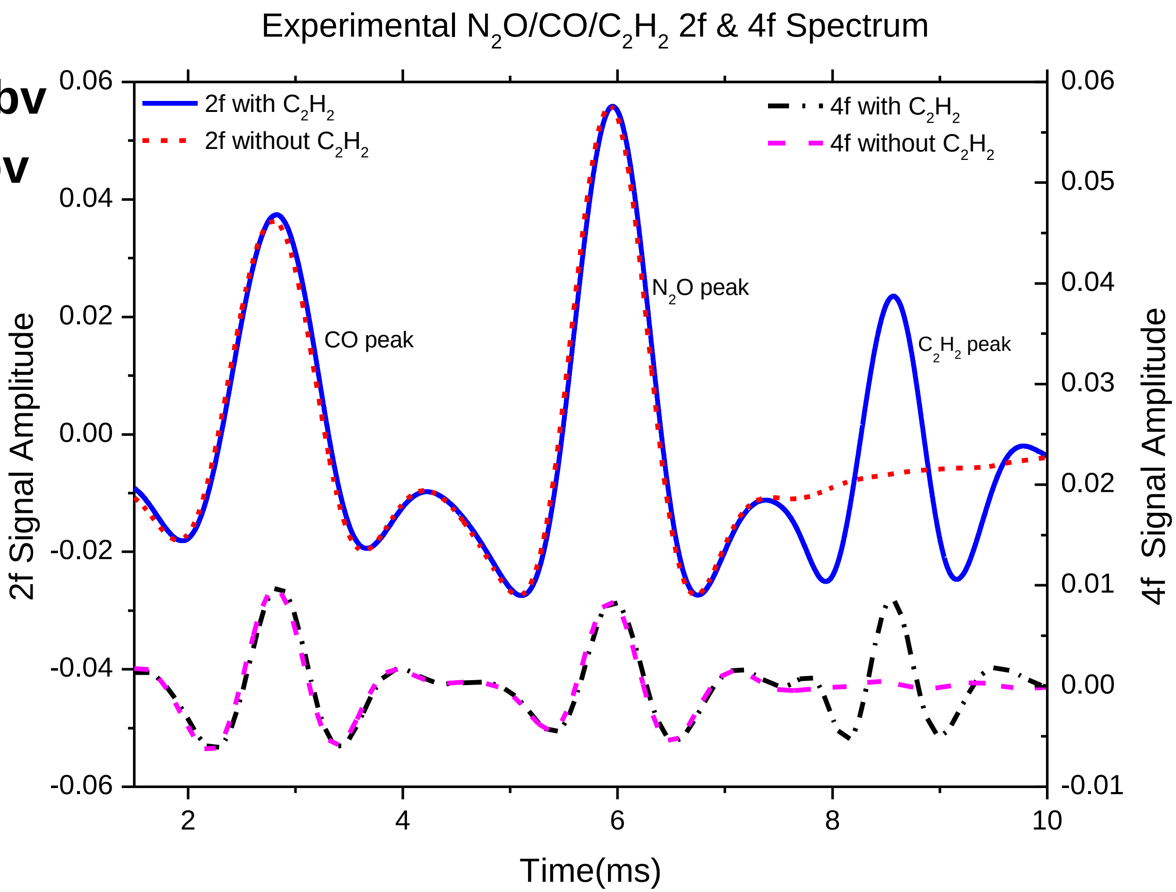
N_2O precision at 1 Hz = 0.06 ppbv

CO precision at 1 Hz = 0.12 ppbv

Multiharmonic in-line maintains calibration of <0.4 ppbv N_2O over 24 hours
y

10 kg, 40 W, 35 x 18 x 15 cm

Tao et al., *Appl. Phys.* B, 2012b



- **CO distinguishes CH_4 from combustion, uncombusted leaks**
- **N_2O, C_2H_2 plume tracers when released at source (emissions)**

Methane UAV laser-based sensing

VCSEL-based UAV sensors

- first flight demonstration of UAV high-performance laser sensors for CH_4, CO_2, H_2O
  ~ 1-2 kg, 2 W for each system alone (unoptimized for mass, power at this point)
- simultaneous detection of CH_4/H_2O or CO_2/H_2O
- high-performance (CH_4: 1.5 ppbv prec., 1 Hz)
- multiharmonic, in-line system accounts for drift, greatly lowers maintenance
- future work: integrated systems, electronics to achieve 1 W, 1 kg for all three gases

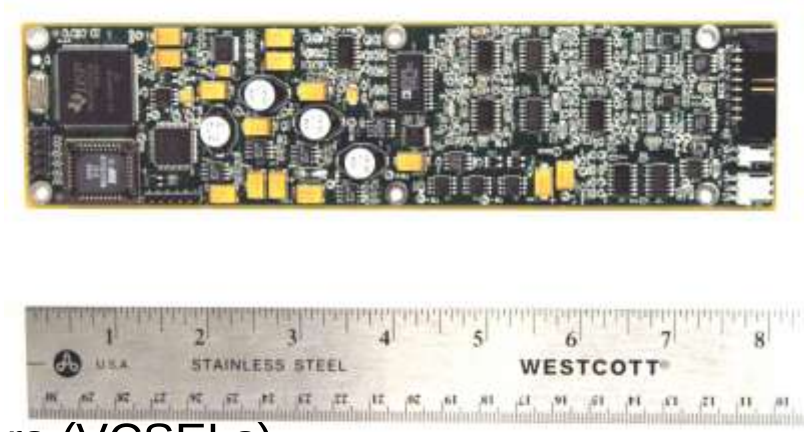
QCL-based sensors

- simultaneous detection of CO, N_2O, and C_2H_2 for tracers to understand CH_4 emissions
- future work: sensors on circuit boards (fibers, waveguides) due to higher sensitivities

Low power, lightweight CH_4 (and other species) sensors excellent for quantifying, fingerprinting fugitive petrochemical emissions from UAVs

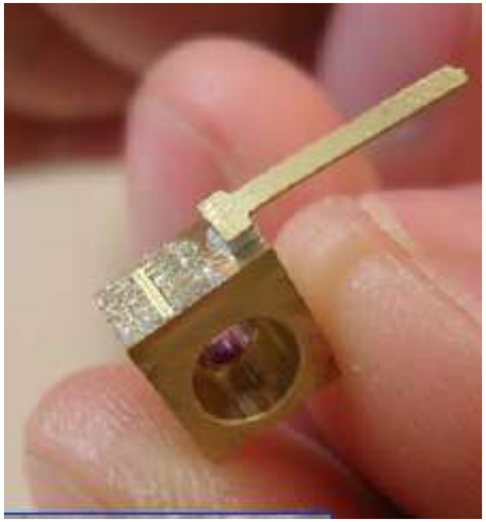
Laser-based sensors for methane emissions

Innovative detection schemes of newly-developed technologies:



1. Attributes of laser-based detection
   - Beer-Lambert law
   - Multi-harmonic in-line reference stability
   - Open-path (no pumps ➔ low power)

2. Near infrared vertical cavity surface emitting lasers (VCSELs)
   - Methane, 1651 nm
   - Carbon dioxide, 2004 nm
   - Water vapor, 1854 nm



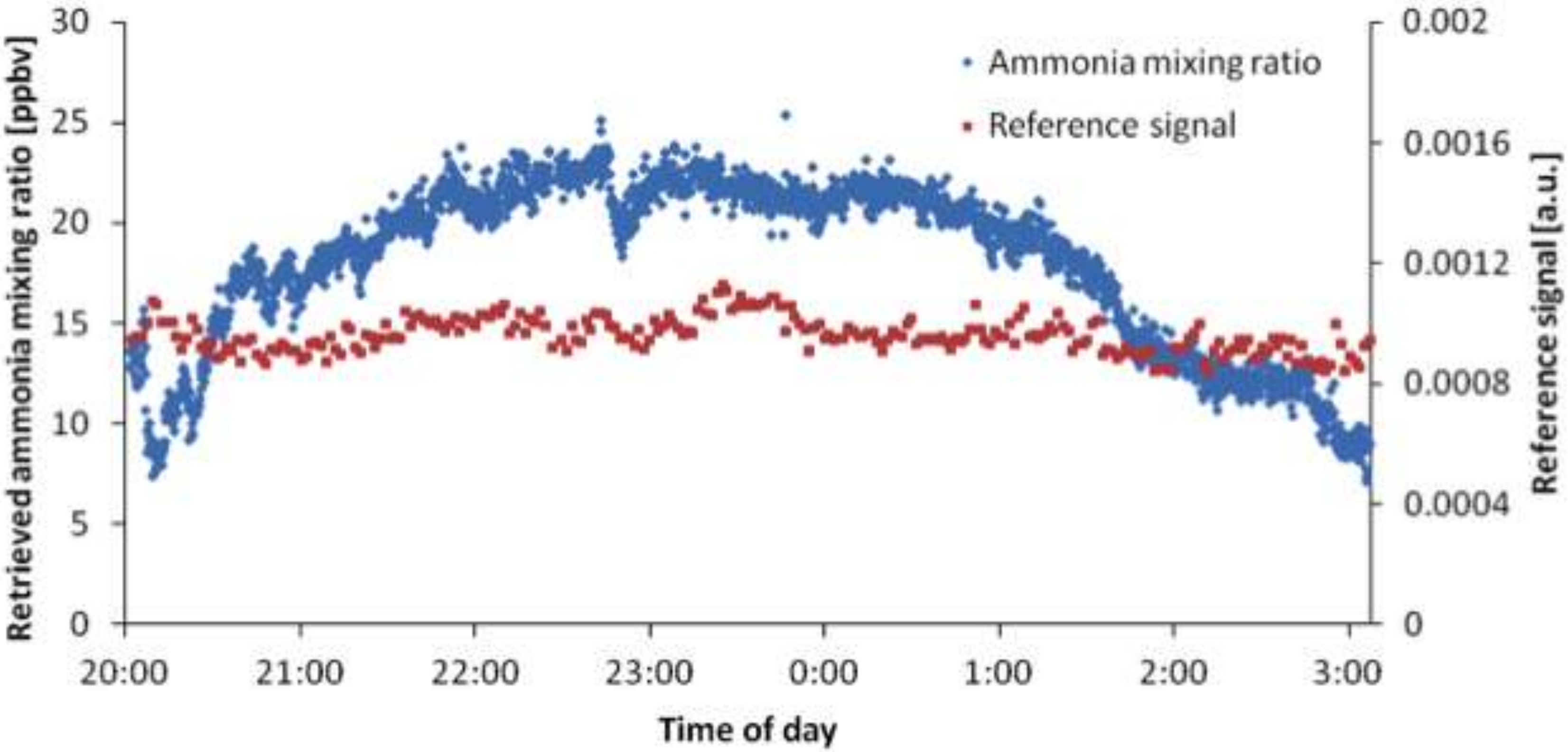
3. Quantum cascade lasers (QCLs)
   - Carbon monoxide/nitrous oxide/acetylene, 4.5 µm
   - Ammonia/ethylene, 9.1 µm

Merging of innovative optical devices and schemes with future airborne platforms!

- also of use in smartphone apps, remote locations, sensor networks, balloons, tethered balloons, kites

Ammonia in-line reference signal

Sun et al., Appl. Phys. B, 2012

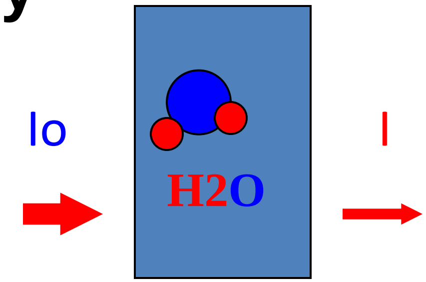


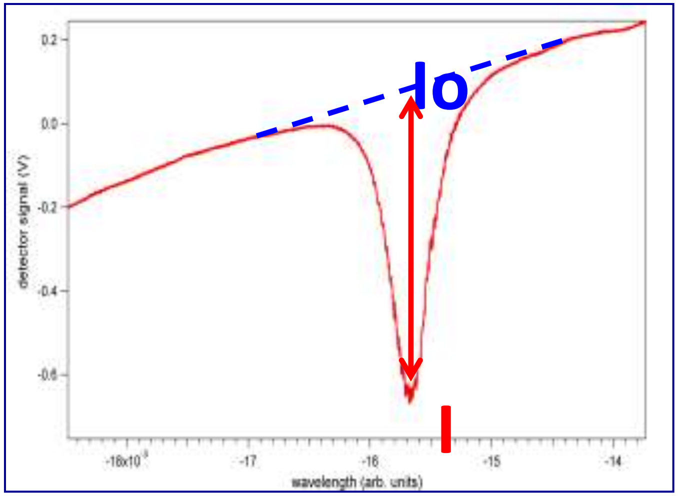
- Reference signal stable to <4% over range factor three in ambient concentration

- Multiharmonic, numerical fitting algorithm isolates NH_3, ref. signals

Laser absorption spectroscopy

$$\frac{I(\lambda)}{I_o(\lambda)} = \exp(-\alpha(\lambda))$$





where: $I(\lambda)$ is light intensity after absorption

$Io(\lambda)$ is incident light intensity

$\alpha(\lambda)$ is absorbance

$$a(\lambda) = S(T)\, g(\lambda,T,P)\, N\, l$$

σ = cross section

where: $S(T)$ is the linestrength

$g(\lambda,T,P)$ is the normalized Voigt lineshape function

N is the absolute concentration

l is the pathlength

• we use combination of direct absorption and multi-harmonic wavelength modulation techniques with open-path configurations (no pumps)

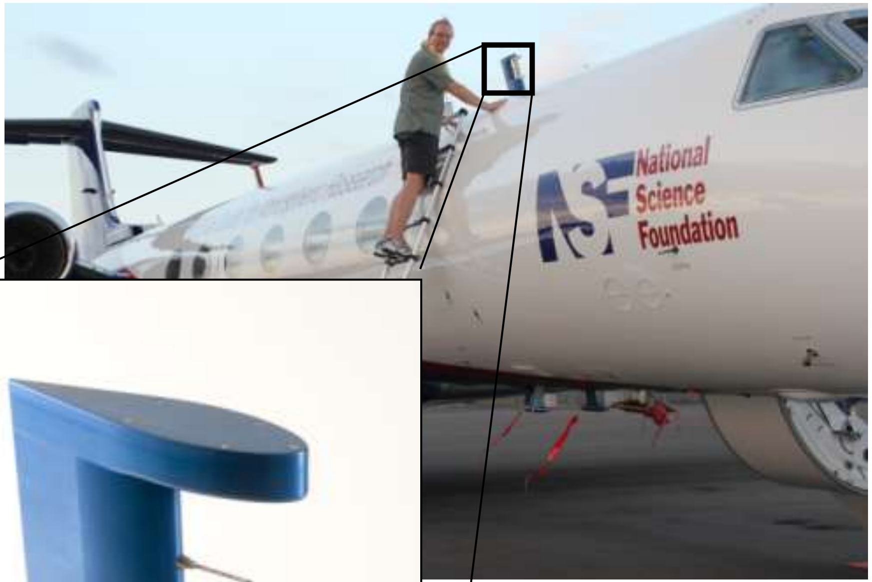
• sensitive, selective, fast-response

NSF Gulfstream-V VCSEL hygrometer

Vertical Cavity Surface Emitting Laser, 1854 nm

(Zondlo et al., JGR, 2010)

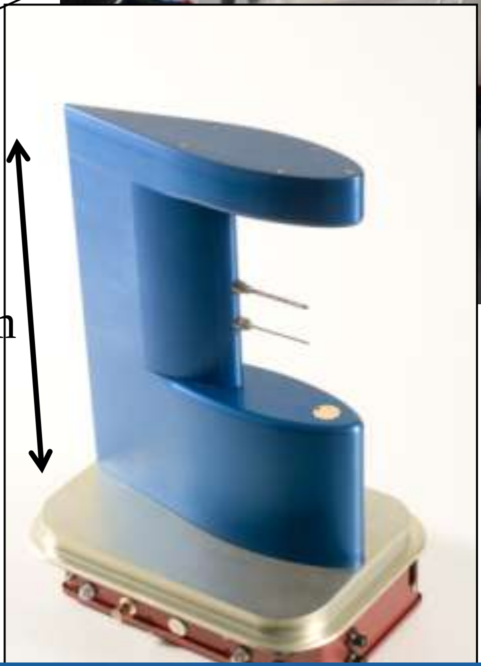
~ 700 flight hours, routine on NSF G-V (since 2008)



1854 nm fiberized VCSEL, WMS and direct abs.

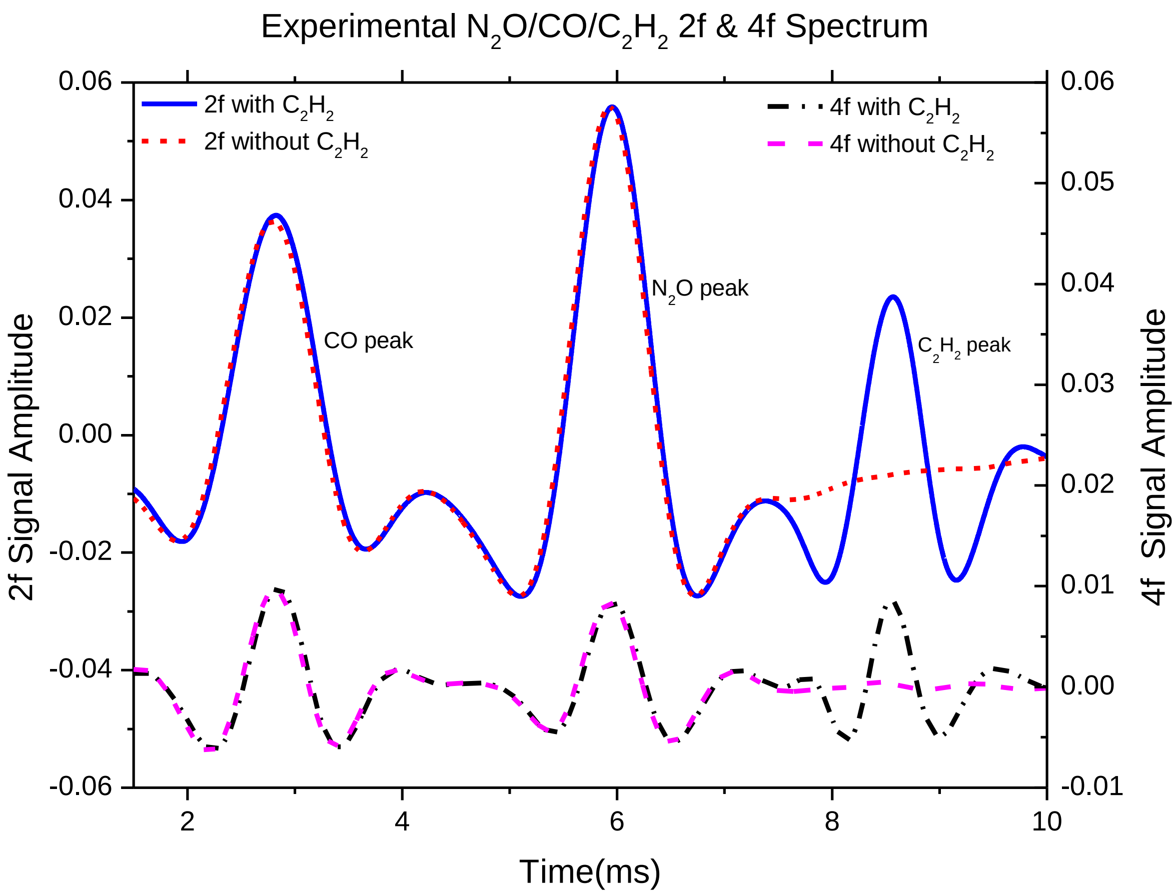
Parameter	Specifications
Dew point range	-110°C to +30°C
Sensitivity (1 Hz)	0.05 ppmv
Frequency	25 Hz
Accuracy	2-10%
Precision	≤ 1%
Power	8 W
Weight	6 kg
Size	25 cm × 16 cm × 5 cm
Operation	unattended
Design	open-path

29 cm



- VCSEL hygrometer is open-path
  25 pass Herriott cell: 3.74 m path; mirror radius=0.95 cm; 14.95 cm mirror separation)
- 99.3% data coverage on global campaign from the Arctic to tropics to Antarctic, surface to the stratosphere

Multiharmonic in-line stability signal



Accuracy maintained <0.4 ppbv for 24 hours

- C_2H_2 Reference Cell: 50 Torr, 3 cm-long 100% C_2H_2
- C_2H_2 peak serves as continuous reference signal to account for system drift (which ultimately determines accuracy)
- higher harmonic (4f) detection isolates absorption lines at ambient pressures
- absolute calibration by NOAA GMD / WMO standards (0.07 ppbv accuracy)

Open-path Atmospheric Ammonia Sensing

Tao et al., Optics Express, 2012; Sun et al., Appl. Phys B, 2012

- 50 W power incl. laptop
- 300 pptv detection limit (1 Hz)
- field tested in desert, snow, rain, etc.

Challenges:

- Interference from other species, i.e. H_2O, CO_2
- Difficult to get the baseline of air-broadened absorption
- Have no control of temperature/pressure
- Calibration: need to enclose the open-path system

Solutions:

- ✓ Detecting ammonia line at 9.06 µm – QC laser (more isolated)
- ✓ Wavelength modulation spectroscopy (WMS)
- ✓ T/P spectroscopic studies
- ✓ In-line ethylene calibration